Design of Piles in France following Eurocode 7

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ABSTRACT : After mentioning the important aspects of pile design following Eurocode 7 (EN 1997-1) and briefly listing the contents of the present French standard for deep foundations (NF P94-262, 2012), this paper focuses on the ULS bearing capacity from PMT and from CPT results and the assessment of the corresponding 'model factors' γ_{Rd} given in the French standard. The PMT methods for predicting the displacements under axial loads ("t-z" method) and under transverse loads ("p-y" method) are also briefly described. More details and experimental background are given by Burlon et al. (2014) and Frank (2017).

1. Aspects of pile design following Eurocode 7 – Part 1 (EN 1997-1, Section 7)

1.1 According to Eurocode 7, the capacity of piles (ultimate compressive or tensile « resistance »), has to be based on:
a) the results of static load tests;
b) empirical or analytical calculation methods validated by static load tests in comparable situations;
c) results of dynamic load tests of which the validity has been demonstrated by static load tests in comparable situations;
d) the observed performance of a comparable pile foundation (to be supported by site investigation and ground testing).

1.2 The characteristic and design axial resistances are derived from measured values R_m or calculated values R_{mod} in the following manner (corresponding to Design Approach 2 offered by Eurocode 7).

Characteristic value:

$$R_k = R / \xi \quad \text{where } R = R_m \text{ or } R = R_{mod}/\gamma_{Rd} \qquad (1)$$

Design value:

$$R_d = R_k/\gamma_t \quad \text{or} \quad R_d = R_{bk}/\gamma_b + R_{sk}/\gamma_s \qquad (2)$$

where ξ are the correlation factors depending on the number of pile load tests or number of ground test profiles, γ are the partial factors on the total pile resistance or on the components of the pile resistance and γ_{Rd} the model factor to correct the calculation method.

Given the applied compression/tension design load:

$$F_d = \gamma_F F_k \qquad (3)$$

and

the general condition for ULS:

$$F_d \leq R_d \qquad (4)$$

equations (1) to (4) lead to:

$$F_k \leq R_m / \gamma_F.\gamma_t.\xi \quad \text{or} \quad F_k \leq R_{mod}/\gamma_{Rd}.\gamma_F.\gamma_t.\xi \qquad (5)$$

The multiplication of factors $\gamma_{Rd}.\gamma_F.\gamma_t.\xi$ can be perceived as corresponding to the traditional 'global' safety factor.

1.3 Actions on piles due to ground displacement:
* the ground displacement is treated as an action and an interaction analysis is carried out (e g: transverse thrusts)
or
* an upper bound of the force transmitted by the ground is introduced as the design action (e g: negative friction).

In these calculations, the design values of the strength and stiffness of the moving ground should usually be upper values.

1.4 In summary, the main features for designing pile foundations with Eurocode 7 are:
* the importance of static pile load tests;
* an innovative procedure to pile capacity taking account of number of load tests or number of soil profiles (through the ξ values);
* the importance of assessing displacements of foundations, in particular for ensuring the serviceability of structures.

2. Table of contents of the French standard for the Application of Eurocode 7

The standard NF P 94-762 was published in July 2012.

It contains 15 sections and 19 annexes. It is 206 pages long (98+108).

The main sections are devoted to the following topics: combinations of actions and action effects, ultimate compressive resistance (bearing capacity), ultimate tensile resistance, resistance to transverse loadings, structural resistance (concrete and steel properties for piles), overall stability, and verifications of serviceability limit states.

Normative annexes deal with values of partial factors, bearing capacity and tensile resistance from pressuremeter tests (PMT) results and from CPT results. The main informative annexes are devoted to types of piles, soil categories, static pile load tests and bearing capacity, negative friction (downdrag), transverse behaviour, (axial) group effect, horizontal soil displacement, axial stiffness (settlement of piles), movements of foundations, provision for bridges.

3. ULS resistance from PMT and from CPT (assessment of 'model factors' γ_{Rd})

3.1 The background for establishing a 'model factor' γ_{Rd} for piles comes from Eurocode 7 (Section 7 of EN 1997-1). The code
- requires that the validity of calculation methods be demonstrated by static load tests in comparable situation;
- advocates the introduction of an explicit 'model factor' γ_{Rd} (applied to the calculation model) when designing piles from ground test results.

Based on the results of some 174 full scale static load tests in the database of IFSTTAR (formerly LCPC), model factors have been established for the calculation methods of the ultimate compression resistance (bearing capacity) and ultimate tensile resistance from PMT results and from CPT results offered by the French standard.

3.2 The PMT method for ultimate resistance calculation

Pressuremeter rules: base resistance

The base unit resistance is:

$q_p = q_o + k_p (p_{le} - p_o)$

where p_o and q_o are the total horizontal and vertical 'at rest' pressures, p_{le} is the equivalent limit pressure from the PMT at the base and k_p is the bearing factor. k_p is a function of soil type and pile class (there are 7 classes of piles). It varies between 1.0 and 3.2.

Pressuremeter rules: shaft resistance

The unit limit friction is:

$q_s = \alpha . f_{sol}$ and $q_s \leq q_{smax}$

with

$0,4 \leq \alpha \leq 3,8$ and q_{smax} vary according to soil type and pile category (there are 20 pile categories). The function f_{sol} only depends on the type of soil (Figure 1).

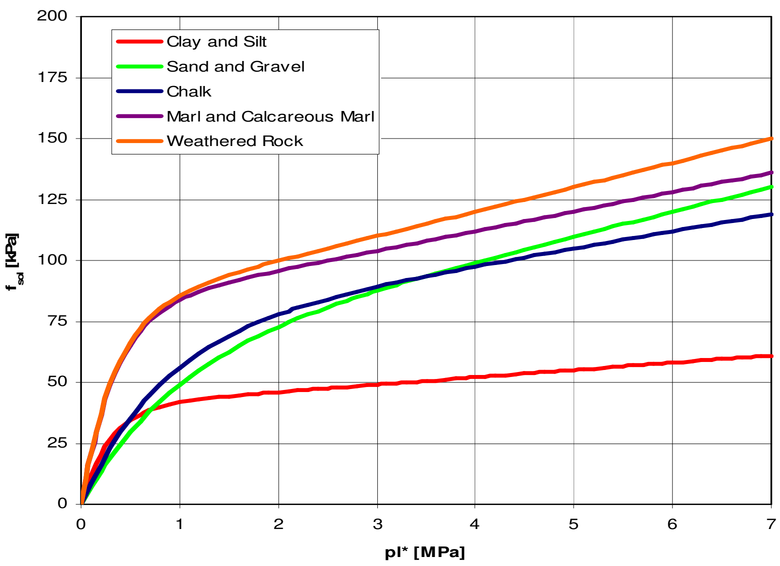

Figure 1. Functions f_{sol} for PMT rules (2012).

For this calculation model leading to the ultimate resistance of piles R_{mod} from PMT results (PMT 2012), values of the model factor (noted $\gamma_{Rd;1}$) have been derived. Figure 2 shows how the value $\gamma_{rd;1}$ = 1,15 was selected for piles of 'group 1' (no injected piles; no chalk) for which 134 tests are available.

The model factors $\gamma_{Rd;1}$ are given in Table 1. They are to be used with the correlation factors ξ ('model pile' procedure). In the case the 'alternative procedure' of Eurocode 7 is used (also called the 'ground model' procedure), the French code requires introducing the additional factor: $\gamma_{Rd;2}$ = 1,1.

For more details, see Burlon et al. (2014) and Frank (2017).

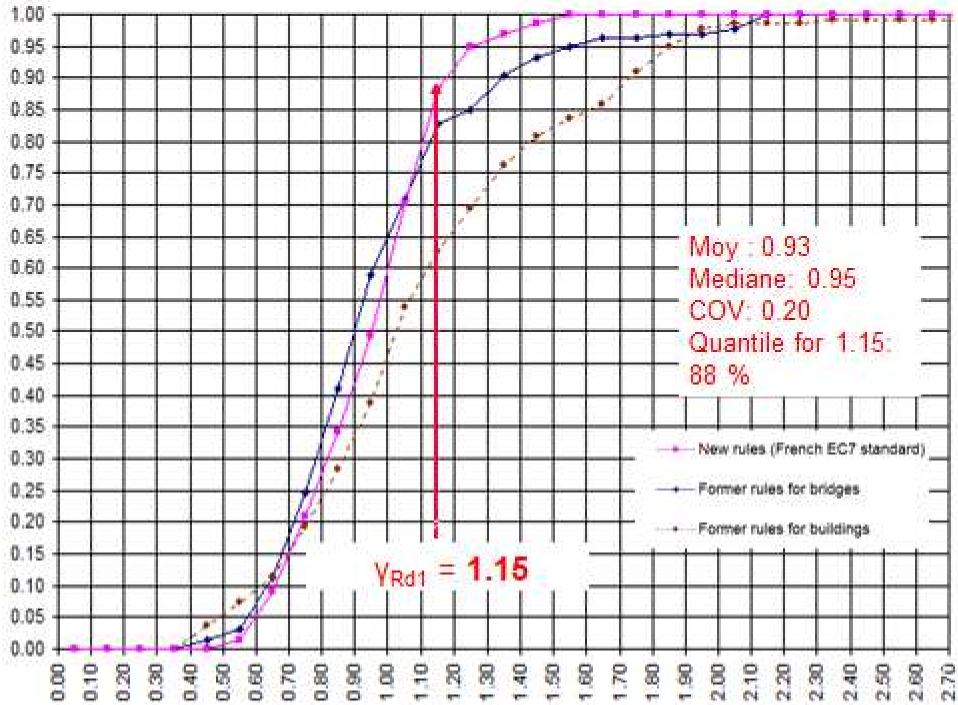

Figure 2. Distribution function of R/R_m for 'group 1' (134 tests, no injected piles; no chalk), Burlon et al. (2014). R = calculated resistance R_m = measured resistance.

Table 1. Values of the model factor $\gamma_{R;d1}$ in the French code for deep foundation (AFNOR, 2012). PMT method.

	$\gamma_{R;d1}$ Compression	$\gamma_{R;d1}$ Tension
All piles, excepted injected piles and piles embedded in chalk	1,15	1,4
Piles embedded in chalk, excepted injected piles	1,4	1,7
Injected piles	2,0	2,0

3.3 The CPT method for ultimate resistance calculation

CPT rules: base resistance

The base unit resistance is:

$q_p = q_o + k_c\, q_{ce}$

where q_o is the total vertical 'at rest' pressure, q_{ce} is the equivalent cone resistance at the base and k_c is the bearing factor. k_c is a function of soil type and pile class (there are 7 classes of piles). It varies between 0.15 and 0.5.

CPT rules: shaft resistance

The unit limit friction is:

$q_s = \alpha\, f_{sol}$ and $q_s \leq q_{smax}$

with

$0{,}2 \leq \alpha \leq 2{,}25$ and q_{smax} vary according to soil type and pile category (there are 20 pile categories). The function f_{sol} only depends on the type of soil (Figure 3).

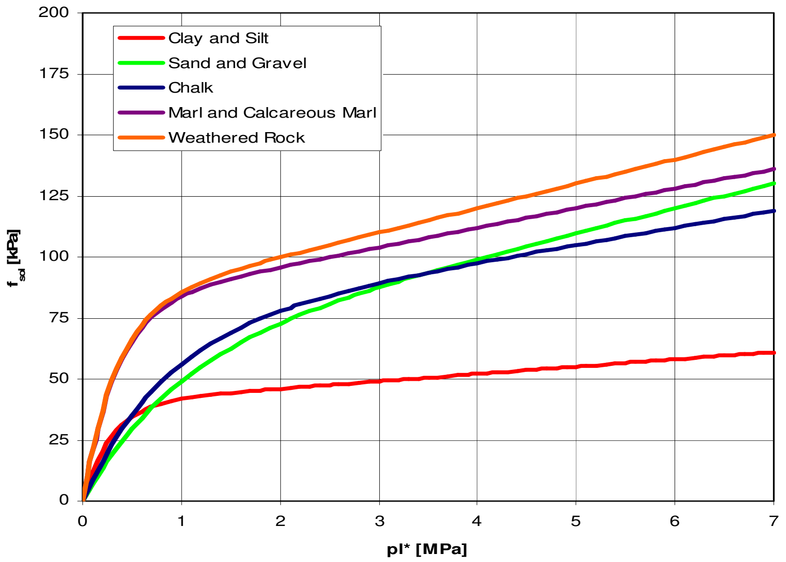

Figure 3. Functions f_{sol} for CPT rules (2012).

For the CPT calculation model of the ultimate resistance of piles R_{mod}, values of the model factor (noted $\gamma_{Rd;1}$) have been derived in a similar manner as for the PMT model. They are given in Table 2. They are to be used with the correlation factors ξ ('model pile' procedure). In the case the 'alternative procedure' of Eurocode 7 is used (also called the 'ground model' procedure), the French code requires introducing and additional factor $\gamma_{Rd;2} = 1{,}1$.

For more details, see Frank (2017).

Table 2. Values of the model factor $\gamma_{R;d1}$ in the French code for deep foundation (AFNOR, 2012). CPT method.

	$\gamma_{R;d1}$ Compression	$\gamma_{R;d1}$ Tension
All piles, excepted injected piles and piles embedded in chalk	1,18	1,45
Piles embedded in chalk, excepted injected piles	1,45	1,75
Injected piles	2,0	2,0

3.4 Design value of the ULS compressive (or tensile) resistance

The design value R_d of the ULS compressive (or tensile) resistance calculated from ground test results (PMT or CPT results or else), is derived from the characteristic resistance R_k and by applying the resistance factor γ_t (Design Approach 2 of Eurocode 7).

The following expressions are obtained, where R_{mod} is the calculated resistance (from the ground test results):

<u>'Model pile' procedure</u>:

$R_d = R_k/\gamma_t = R_{mod}/(\gamma_{R;d1}.\xi.\gamma_t)$, with ξ the correlation factor

<u>'Alternative' procedure ('ground model')</u>:

$R_d = R_k/\gamma_t = R_{mod}/(\gamma_{R;d1}.\gamma_{R;d2}.\gamma_t)$, with $\gamma_{R;d2} = 1,1$

where the resistance factor is:

- for permanent and transient design situations:

γ_t = 1,1 for the ultimate compressive resistance (bearing capacity) and γ_t = 1,15 for the ultimate tensile resistance;

- for accidental design situations:

γ_t = 1,0 for the ultimate compressive resistance (bearing capacity) and γ_t = 1,05 for the ultimate tensile resistance;

- for seismic design situations:

γ_t = 1,1 for the ultimate compressive resistance (bearing capacity) and γ_t = 1,15 for the ultimate tensile resistance.

It is to be noted that the French standard for piles also requires that, for serviceability limit states (SLS), the axial loads be lower than the design value of the creep load (which is a given proportion of the calculated characteristic resistance).

4. Displacement under axial loads ("t-z" method) and transverse loads ("p-y" method)

In the French standard, the t-z curves for axial loads and the p-y curves for transverse loads are derived from the PMT results and they make use, in particular, of the Ménard pressuremeter modulus E_M .

For the t-z curves, the model of Frank and Zhao (1982) is used. Figure 4 shows the t-z curve (denoted τ–s), as well as the base load – base displacement curve q-s_p.

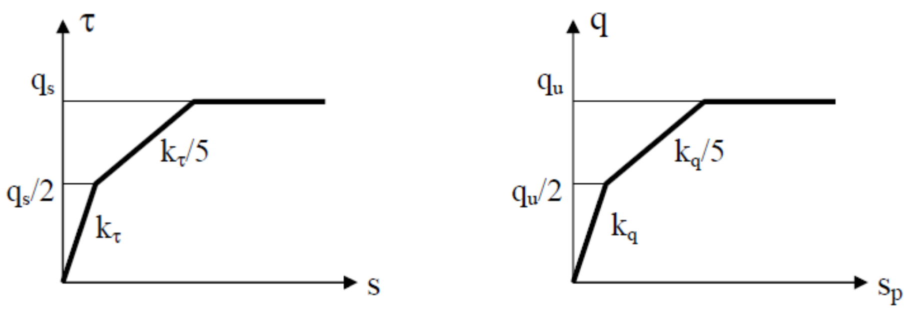

Figure 4. Model for t-z curves (Frank and Zhao, 1982).

The stiffnesses of these curves are,

- for fine grained soils:

$k_\tau = 2.0\ E_M/B$ and $k_q = 11.0\ E_M/B$

- for granular soils:

$k_\tau = 0.8\ E_M/B$ and kq = $4.8\ E_M/B$

Many examples show that the results obtained with this PMT model for deriving the load-settlement of piles is quite satisfactory (see, for instance, Bustamante and Frank, 1999 or Frank, 2017).

As for the determination of the "p-y" curves from PMT results, the French code advocates the use of the traditional Ménard subgrade reaction modulus E_{sM}, as a function of E_M, together with the limit pressure p_l. For more details, see Frank (2017).

5. Conclusions and future developments

In accordance with Eurocode 7 the calculation methods for the bearing capacity of piles, included in the present French standard, are based on the results of full scale load tests on piles.

The new PMT rules for piles (PMT 2012) have been fully calibrated against the database of more than 170 full scale static load tests on piles. Corresponding CPT rules have also been calibrated against the results in the database.

The important role of displacements of foundations of structures is fully recognised in Eurocode 7 and in the French standard. A displacement design approach might prove to be more important than the traditional design based on the determination of the bearing capacity and application of a safety factor.

Are we ready to base our SLS verifications solely on displacement assessments? … and is the structural engineer also ready?

6. Bibliographical references

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